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(54) **ADAPTIVE CHARGING METHOD FOR LITHIUM-ION BATTERY CELLS**

(75) Inventors: **Albert H. Zimmerman**, Torrance;  
**Michael V. Quinzio**, Santa Monica,  
both of CA (US)

(73) Assignee: **The Aerospace Corporation**, El  
Segundo, CA (US)

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(56) **References Cited**

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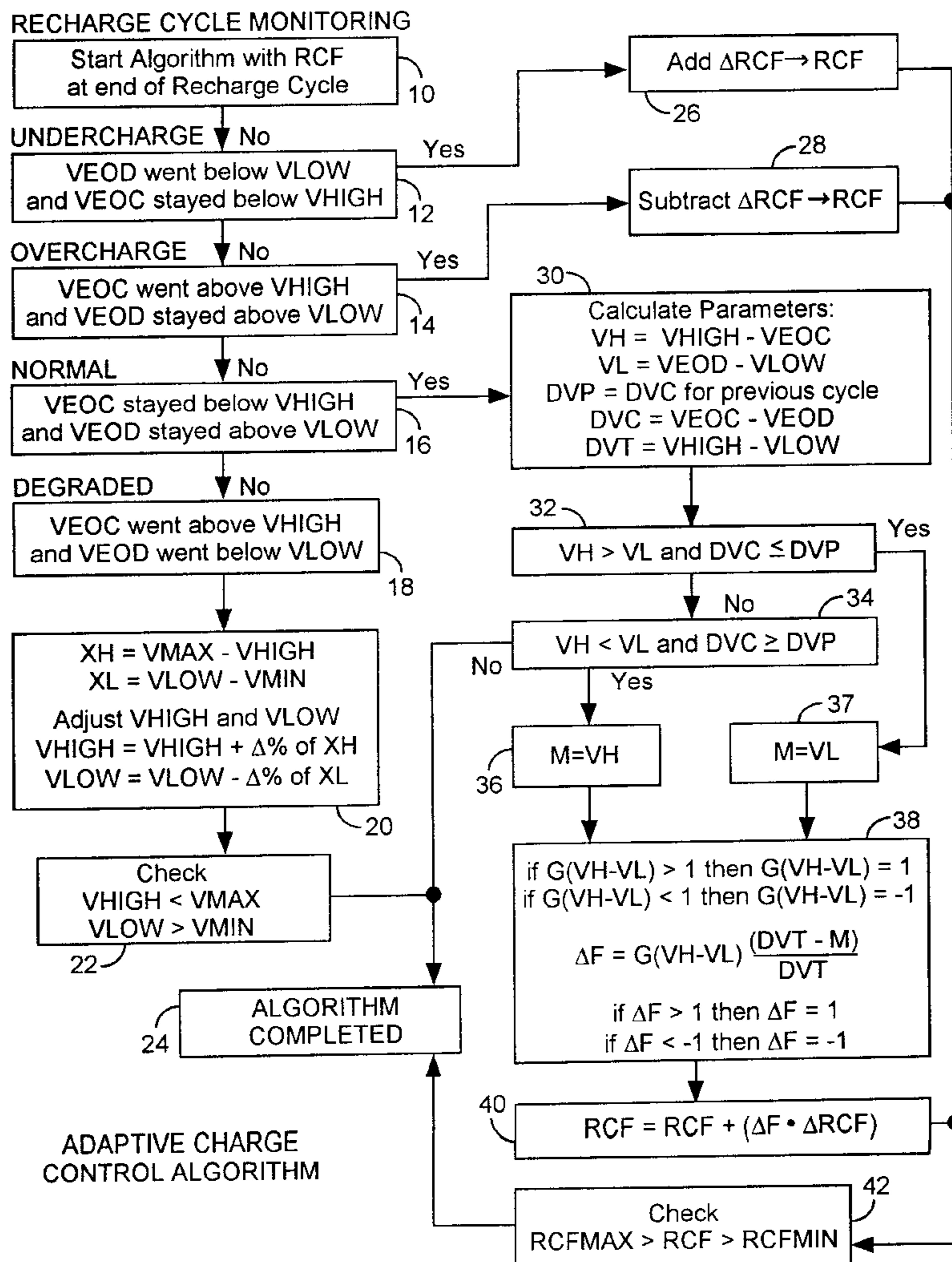
*Primary Examiner*—Edward H. Tso

(74) *Attorney, Agent, or Firm*—Derrick Michael Reid

(57) **ABSTRACT**

A charging and discharging method for lithium-ion and lithium-polymer batteries determines overcharged, undercharged, normal and degraded operating conditions and adjusts a recharge fraction of recharge capacity to discharge capacity for improving battery life while maintaining the battery cells at a high charge state.

**11 Claims, 2 Drawing Sheets**



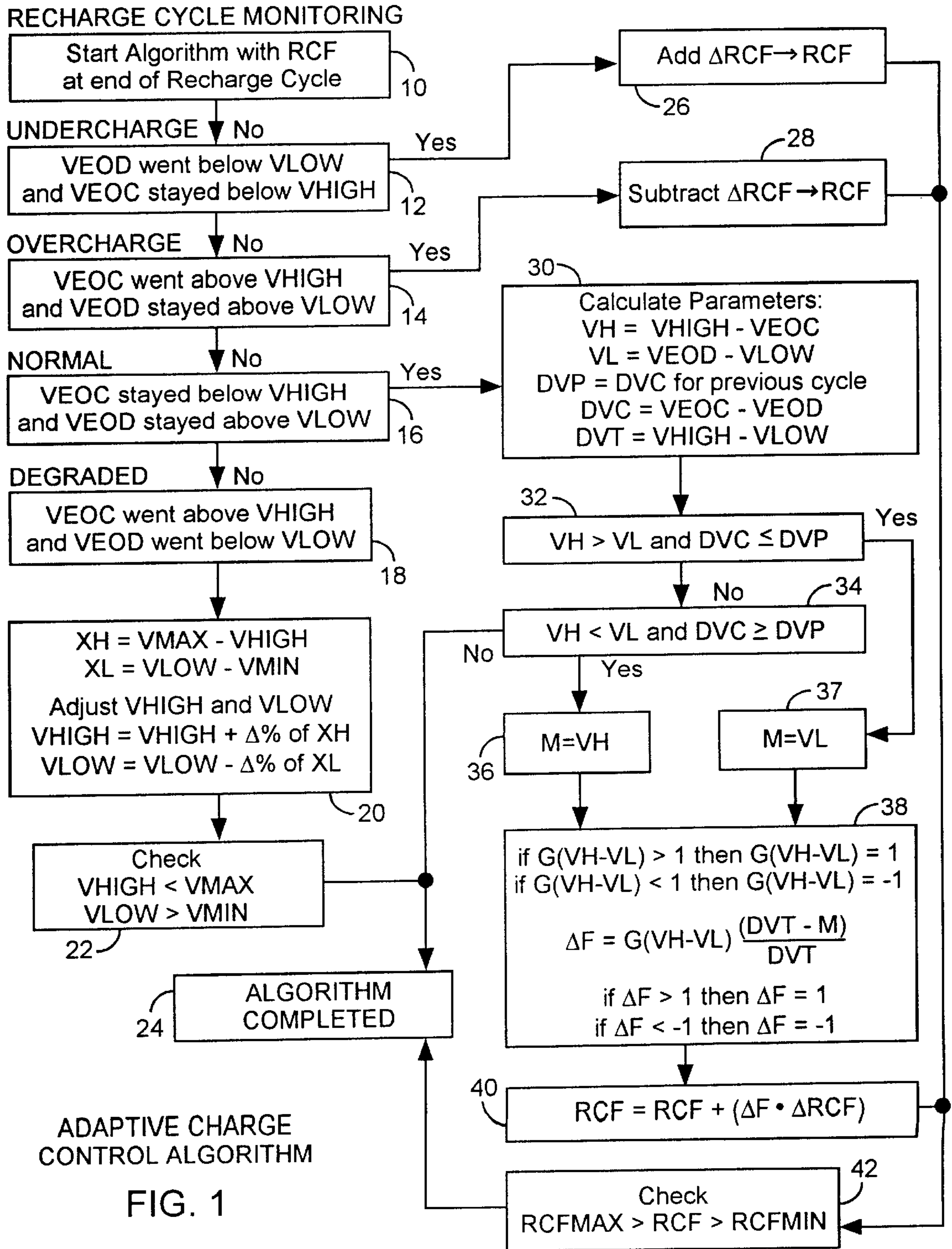
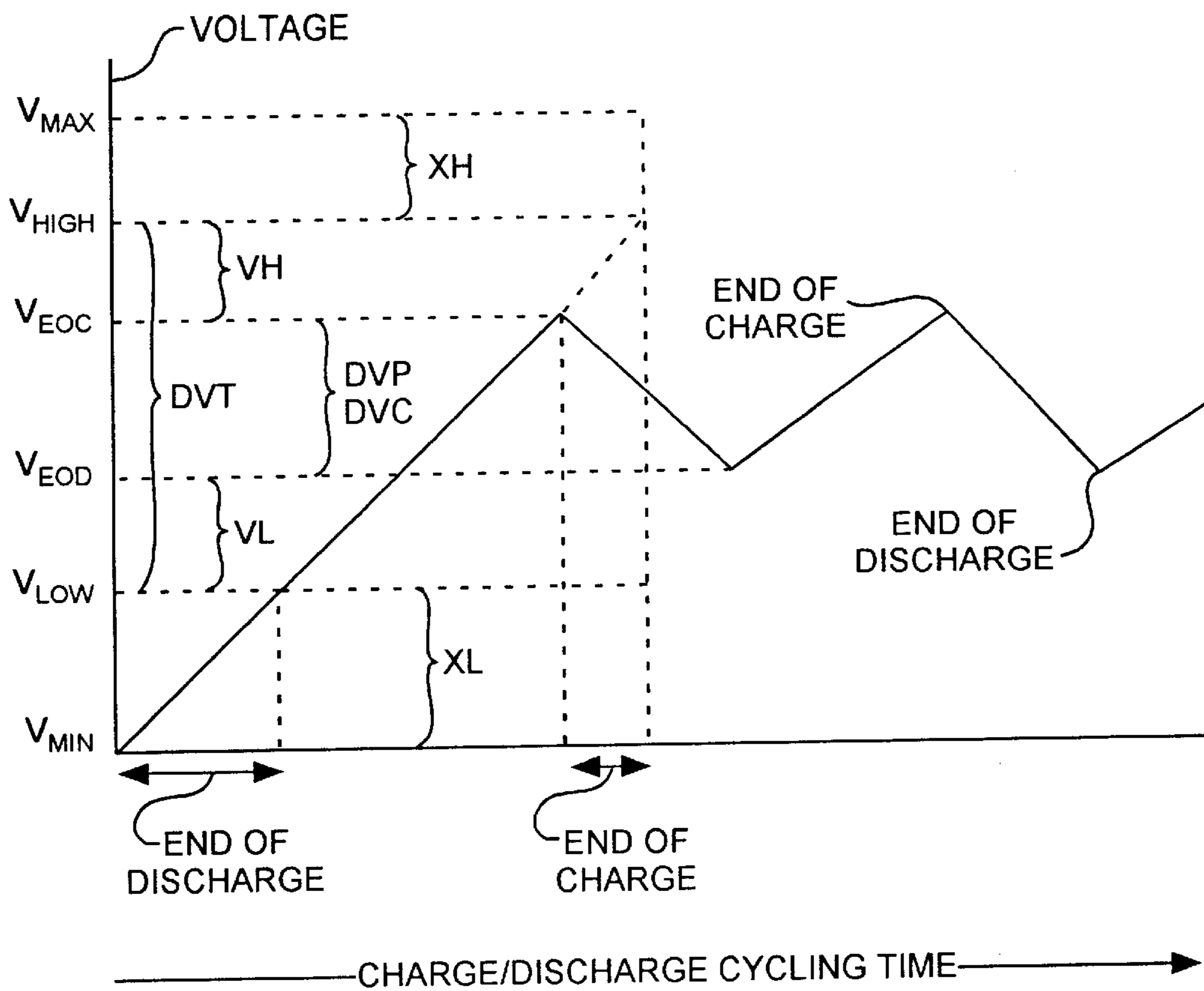


FIG. 1



BATTERY VOLTAGE CYCLES

FIG. 2

D380

## ADAPTIVE CHARGING METHOD FOR LITHIUM-ION BATTERY CELLS

### FIELD OF THE INVENTION

The invention relates to the field of batteries and electrical storage devices. More particularly, the present invention relates to optimum charging of battery cells.

### BACKGROUND OF THE INVENTION

Existing charge control systems for lithium-ion or lithium polymer battery cells typically utilize voltage-limited constant current charging of individual cells to maintain an adequate battery charge while also limiting cell degradation rates. This kind of a charge control system, while adequate for commercial applications that do not have large cycle life requirements, is not capable of optimizing the cycle life capability of lithium-ion and lithium polymer battery cells. Ultimate cycle life has a strong inverse correlation with the cumulative amount of overcharge put into the cells by the charge control system. The optimum cycle life is achieved when unnecessary overcharge is exactly zero. In addition, degradation rates can change significantly as the electrodes transition among several charge states. Also, the recharge voltage limit shifts as the cell temperature changes and as the cells degrade over life. Charge control devices or algorithms that automatically optimize the recharge process and that adapt to changes in the environment or to internal cell degradation are not presently available for lithium-ion and lithium polymer battery cells. These and other disadvantages are solved or reduced using the invention.

### SUMMARY OF THE INVENTION

An object of the invention is to provide a method for adaptively charging battery cells.

Another object of the invention is to provide a method for adaptively charging battery having time varying charge capacities.

Yet another object of the invention is to provide a method for adaptively charging of lithium ion battery cells that have time averaging charge capacities.

A further object of the invention is to provide a method for adaptively charging battery cells by adjusting a recharge fraction parameter that is the amount of charging divided by the amount of discharging over a charging cycle.

The present invention provides an algorithm that meters the correct amount of recharge into a battery cell such as a lithium-ion or a lithium-polymer battery cell, to optimize cycle life, while maintaining the cell at a high state-of-charge. The algorithm automatically adapts to any changes in the thermal environment or any internal cell degradation to maintain the minimum stress condition needed to optimize cycle life. Subtle adaptive changes in the charge control parameters provide an order of magnitude variation in cycle life.

The adaptive algorithm eliminates unnecessary overcharging by metering a charge into each cell and exactly balances the input charge capacity to the discharged capacity. This balance point is adaptively maintained over repetitive cycling by adaptively changing the control parameters reducing cell degradation. Capacity degradation relates to the cell charge and discharge voltages. The adaptive algorithm uses a plurality of control parameters to adaptively adjust the recharge fraction. For example, a low discharge voltage due to capacity degradation is compensated by a slight upward adjustment to the charge into the cell during

recharge. This assures minimum degradation rates while keeping each cell at the maximum state-of-charge consistent with optimum cycle life. The recharge algorithm firstly locates the optimum charge control point for each cell in a battery, and secondly adapts the charge control parameters as the cell degrades or the thermal environment changes so as to maintain the optimum condition for best cycle life. These and other advantages will become more apparent from the following detailed description of the preferred embodiment.

### BRIEF DESCRIPTION OF THE DRAWINGS

FIG. 1 is a graph of charge cycles of a battery.

FIG. 2 is an flow diagram of a battery charge algorithm.

### DETAILED DESCRIPTION OF THE PREFERRED EMBODIMENT

An embodiment of the invention is described with reference to the Figures using reference designations as shown in the Figures. Referring to the Figures, an adaptive charge control algorithm is based on the recognition that a full recharge fraction will provide the optimum cycle life for lithium Ion and lithium polymer battery cells. A full recharge fraction is when the battery is fully recharged to the extent of a prior discharge. This adaptive charge control algorithm provides small adjustments to the optimum recharged fraction to correct for measurement errors and self-discharge, based on high and low voltage trigger levels. The battery cell charge control parameters that are measured are the cell voltage, cell charge current, cell discharge current, charge time and discharge time.

The adaptive charge control parameters are used to implement the adaptive charge control algorithm.

A recharge fraction (RCF) is equal to the ratio of the recharge capacity in Amp-hours during recharge divided by discharge capacity in Amp-hours during discharge.

The recharge capacity is a product of cell charge current and cell charge time. The discharge capacity is a product of the cell discharge current and the cell discharge time.

A recharge fraction adjustment  $\Delta RCF$  is the maximum amount of change to the recharge fraction that can occur from one cycle to the next and is typically a small value.

A recharge fraction adjustment portion  $\Delta F$  is a portion of the maximum recharge fraction adjustment  $\Delta RCF$  that is applied to adjust the recharge fraction from one cycle to the next.

A maximum recharge fraction  $RCF_{Max}$  is the maximum value permitted for the recharge fraction RCF.

A minimum recharge fraction  $RCF_{Min}$  is the minimum value permitted for the recharge fraction RCF.

A low voltage trigger level  $V_{Low}$  triggers adjustment to  $V_{Low}$  on the next charging cycle, triggers adjustments to the RCF for the next charging cycle, and generally indicates capacity degradation.

A high voltage trigger level  $V_{High}$  triggers adjustments to  $V_{High}$  on the next charge cycle, triggers adjustments to the RCF for the charging cycle, and generally indicates an overcharge or degradation condition.

An end of charge voltage  $V_{EOC}$  is the maximum cell voltage during the charge portion of the charge cycle and is typically at a maximum at the end of charge.

An end of discharge, voltage  $V_{EOD}$  is the minimum cell voltage during the discharge portion of the charge cycle and is typically at a minimum at the end of discharge of a charge cycle.

A maximum cell voltage  $V_{Max}$  is the maximum voltage that the cell is permitted to reach at any time during a charge cycle.

A minimum cell voltage  $V_{Min}$  is the minimum cell voltage that the cell is permitted to reach at any time during a charge cycle.

A high voltage margin  $XH$  is the difference between  $V_{Max}$  and  $V_{High}$  and is the margin between the maximum permitted voltage  $V_{Max}$  and the current operating high voltage trigger point  $V_{High}$ .

A low voltage margin  $XL$  is the difference between  $V_{Min}$  and  $V_{Low}$  and is the margin between the minimum permitted voltage  $V_{Min}$  the current operating low voltage trigger point  $V_{Low}$ .

A high trigger margin  $VH$  is the difference between the maximum charge voltage  $VEOC$  and the high trigger voltage  $V_{High}$  and is used to determine the amount of the recharge fraction adjustment  $\Delta RCF$ .

A low trigger margin  $VL$  is the difference between the minimum discharge voltage  $VEOD$  and the low trigger voltage  $\Delta_{Low}$  and is used to determine the amount of the recharge fraction adjustment  $\Delta RCF$ .

The voltage trigger range  $DVT$  is the difference between the high trigger level  $V_{HIGH}$  and the low trigger level  $V_{LOW}$  and is used to compute changes to the recharge fraction.

A trigger level adjustment  $\Delta\%$  is the amount of change to the high voltage margin  $XH$  and the low voltage margin  $XL$  for respectively adjusting the high trigger level  $V_{High}$  and the low trigger level  $V_{Low}$  for the next charge cycle.

The previous voltage charging range  $DVP$  is the charging and discharging range of the previous charging cycle and is equal to the end of charge voltage  $VEOC$  minus the end of discharge voltage  $VEOD$  for the previous charging cycle.

The current voltage charging range  $DVC$  is the charging and discharging voltage range of the current time wise charging cycle and is equal to  $VEOC$  minus  $VEOD$  for the current time wise charging cycle.

The gain  $G$  is a scalar used for computing the recharge fraction adjustment, and is used to determine how much the recharge fraction adjustment changes due to changes in the voltage charge range position  $DVQ$ .

The adaptive charge control algorithm uses the charge control parameters to adaptive recharge and discharge the cell. The recharge fraction being a key recharge parameter. The algorithm starts for any one particular battery cell and is repeated for all of the cells in a battery. The algorithm starts **10** with a predetermined recharge fraction. During each recharge cycle, discharging and recharging battery current and voltages are monitored. At the end of each charge cycle the method adjusts the RCF to maintain optimum charge control in response to cell operating changes.

At initiation **10**, cell voltages and current are monitored during a current recharge cycle during which the cell is recharged to  $VEOC$  and then discharged to  $VEOD$ . The amount of recharge is a recharge fraction of the amount of capacity that was discharged during the previous recharge cycle with  $V_{Low}$  and  $V_{High}$  setting charge trigger margins. Initially, the recharge fraction is set to a full recharge fraction with  $V_{Low}$  and  $V_{High}$  margins set to a predetermined value between  $V_{Max}$  and  $V_{Min}$ .

The recharge algorithm is characterized by four operating conditions, undercharge **12**, overcharge **14**, normal **16** and degraded **18**. In the undercharge condition,  $VEOC$  is below  $V_{High}$  and  $VEOD$  is below  $V_{Low}$ . The battery cell is

undercharged **12** during the recharge cycle when the battery voltage is too low by being below  $V_{Low}$ . In the overcharge condition **14**,  $VEOC$  is above  $V_{High}$  and  $VEOD$  is above  $V_{Low}$ . The battery cell is overcharged **12** during the recharge cycle when the battery voltage went too low by being below  $V_{Low}$ . In the normal operating condition **16**, the  $VEOC$  is below  $V_{High}$  and  $VEOD$  is above  $V_{Low}$ . The battery cell is operating normally **16** during the recharge cycle when the battery voltage went neither too high by being below  $V_{High}$  nor too low by being above  $V_{Low}$ . In the degraded condition **18**,  $VEOC$  is above  $V_{High}$  and  $VEOD$  is below  $V_{Low}$ . The battery cell is degraded during the recharge cycle when the battery voltage went too high by being above  $V_{High}$  and went too low by being below  $V_{Low}$ .

When the battery cell degraded **18**, the  $XH$  and  $XL$  margins are computed **18** and the  $V_{High}$  and  $V_{Low}$  triggers are adjusted **20**. The  $V_{High}$  trigger is adjusted to  $V_{High}$  plus  $\Delta\%V_{High}$ . The  $V_{Low}$  trigger is adjusted to  $V_{Low}$  minus  $\Delta\%V_{Low}$ . The adjustments to the  $V_{High}$  and  $V_{Low}$  triggers serves to increase the operating recharge and discharge trigger levels in the presence of degradation of the battery cell. The  $\Delta\%$  is preferably a predetermined  $\Delta V$  voltage incremental value or percentage, for example,  $\Delta\%$  may be 2 mv. The  $XH$  and  $XL$  margins are compared **22** to verify that  $V_{High}$  is below  $V_{Max}$  and  $V_{LOW}$  is greater than  $V_{Min}$  so that the battery recharged  $VEOC$  voltage and discharge  $VEOD$  voltage are within the maximum and minimum allowable voltages  $V_{Max}$  and  $V_{min}$ . After comparison, the algorithm is completed **24** in advance of the next recharge cycle **10**.

In the degraded condition **18**, the algorithm may be further modified to enable differing values of  $\Delta\%$  applied to the adjustment of  $V_{High}$  and  $V_{Low}$ . For example, when in the degraded condition, and when  $V_{High}$  is less than 3.9 volts,  $V_{High}$  is increased by  $\Delta\%$ , which may be 10 mv with no change to  $V_{LOW}$ . When  $V_{High}$  is between 3.9V to 4.1V,  $V_{High}$  is increased 5 mv and  $V_{LOW}$  is decreased 5 mv. When  $V_{High}$  is greater than 4.1V, there is no change to  $V_{High}$  and  $V_{Low}$  is decreased by 10 mv. In this manner, the degradation adjustments  $\Delta\%$  are variable values, and can depend, for example, on the present value of  $V_{High}$ .

In the undercharge condition **12**, the recharge fraction RCF is increase **26** by the recharge fraction adjustment  $\Delta RCF$ . In the overcharged condition, RCF is decreased by  $\Delta RCF$ . The recharge fraction adjustment may be a predetermined voltage value or percentage, for example, the recharge fraction adjustment may be 0.02%. Additionally, the algorithms may be modified to not apply the recharge fraction adjustment  $\Delta RCF$  **26** when in the undercharged condition **12** when  $VEOC$  has dropped  $\Delta\%$  since the last recharge cycle, or not apply the recharge fraction adjustment  $\Delta RCF$  **28** when in the overcharged condition **12** when  $VEOD$  has increased  $\Delta\%$  since the last discharge cycle. The adjustments  $\Delta RCF$  to the recharge fraction RCF is used to reduce recharging **28** when in the overcharged condition **14** and to increase charging **26** when in the undercharge condition **12**.

When in the normal operating condition **16**, the algorithm serves to center the current charging range  $DVC$  between the trigger levels  $V_{High}$  and  $V_{Low}$  by making adjustments to the recharge fraction. The parameters  $VH$ ,  $VL$ ,  $DVC$ , and  $DVT$  are computed **30** with  $DVP$  being the charging range of the previous recharge cycle. When  $VH$  greater than  $VL$  and  $DVC$  is less than or equal to  $DCP$  **32**, the margin  $M$  is set **37** to  $VL$ . This indicates that charging range is decreasing, that the charging range is not centered, that the low margin  $VL$  is the lesser of the two margins, and that the

center position of the charging range is decreasing. When  $V_H$  is lesser than  $V_L$  and  $DVC$  is greater than or equal to  $DCP$  **34**, the margin  $M$  is set **36** to  $V_H$ . This indicates that the charging range is increasing, that the charging range is not centered, that the high margin  $V_H$  is the lesser of the two margins  $V_H$  and  $V_L$ , and that the center position of the charging range is increasing. When neither of these two conditions are met, the algorithm terminates **24** without adjusting the recharge fraction  $RCF$  to center the charging range for the next cycle between the trigger level  $V_{High}$  and  $V_{Low}$ .

In either case of increasing or decreasing charging range in the respective presence of an increasing  $V_L$  or decreasing  $V_H$ , the recharge fraction adjustment portion  $\Delta F$  is computed **38** for adjusting the recharge fraction  $RCF$  **40** serving to respectively decrease or increase the voltage charging so as to recenter the voltage charging range between the  $V_{High}$  and  $V_{Low}$  triggers. The recharge fraction adjustment portion is equal to the product of two terms. The first term is gain  $G$  times the difference between the high and low margins, which provides for a margin differential portion ( $V_H - V_L$ ). The margin differential portion is limited to +1 when exceeding a +1 value and limited to -1 when succeeding a -1 value. The second term is the charge range minus the less margin  $M$  with this result divided by the charge range indicating an available charging range. Hence, the recharge adjustment portion  $\Delta F$  is a product of the margin differential portion and the available charging range. The recharge adjustment portion  $\Delta F$  is also limited to a +1 value when exceeding +1 and limited to a -1 value when succeeding -1. The computed **38** recharge fraction portion  $\Delta F$  is used to adjust **40** the recharge fraction  $RCF$  by the recharge fraction adjustment portion  $\Delta F$  multiplied by the recharge fraction adjustment  $\Delta RCF$ . After adjustment of the  $RCF$  **40**, a check **42** is made to limit the values of the  $RCF$  between  $RCF_{Max}$  and  $RCF_{min}$ .

As may now be apparent, the algorithm increases the  $RCF$  in the presence of an undercharge condition **12** to increase the  $VEOD$ , decreases the  $RCF$  in the presence of an overcharge condition **14** to decrease the  $VEOC$ , increases or decreases the  $RCF$  to center the charging range in the presence of a normal condition **16**, and increases the high margin  $V_H$  and decreases the low margin  $V_L$  to increase the charging range in the presence of a degraded condition. The algorithm serves to adaptively maintain the charge of the battery cell over the operating conditions. The algorithm is preferably applied to battery cells for which long battery cycle life is critical, such as for low-earth-orbit satellite applications where long cycle battery life is critical. Those skilled in the art can make enhancements, improvements, and modifications to the invention, and these enhancements, improvements, and modifications may nonetheless fall within the spirit and scope of the following claims.

What is claimed is:

1. A charging method for charging and discharging a battery cell during recharge cycles, the method comprising the steps of

monitoring the battery cell during a recharge cycle for determining an end of charge voltage ( $VEOC$ ) during recharging of the battery cell and an end of discharge voltage ( $VEOD$ ) during the discharging of the battery cell, the recharge cycle serving to charge the battery cell with capacity equal to a recharge fraction ( $RCF$ ) amount of the amount of discharging capacity,

determining an undercharge condition of the battery cell when the  $VEOD$  went below a low trigger level ( $V_{High}$ ) during the discharging and the  $VCOE$  stayed below a high trigger level ( $V_{High}$ ) during the recharging,

increasing the  $RCF$  for a next cycle of the recharge cycle when in an undercharge condition,

determining an undercharge condition of the battery cell when the  $VEOC$  went above  $V_{High}$  during the recharging and the  $VCOD$  stayed above the  $V_{Low}$  during the discharging,

decreasing the  $RCF$  for a next cycle of the recharge cycle when in an overcharge condition,

determining a degraded condition of the battery cell when the  $VEOC$  went above  $V_{High}$  during the recharging and  $VEOD$  went above  $V_{Low}$  during the discharging,

increasing the  $V_{High}$  and decreasing  $V_{Low}$  when in the degraded condition serving to increase a trigger range ( $DVT$ ) being a difference between  $V_{High}$  and  $V_{Low}$  ( $DVT = V_{High} - V_{Low}$ ),

determining a normal condition of the battery cell when  $VEOC$  stayed below  $V_{High}$  during recharging and  $VEOD$  stayed above  $V_{Low}$  during discharging, and

adjusting the  $RCF$  to center a voltage range being a difference between  $VEOC$  to  $VCOD$  within the trigger range.

2. The method of claim 1 wherein  $VEOC$  is equal to a highest voltage charge level of the battery cell during the recharging of the battery cell.

3. The method of claim 1 wherein  $VEOC$  is equal to a lowest voltage charge level of the battery cell during the discharging of the battery cell.

4. The method of claim 1 wherein,

the increasing the  $RCF$  step increases the  $RCF$  by a predetermined recharge fraction adjustment ( $\Delta RCF$ ), and

the decreasing the  $RCF$  step decreases the  $RCF$  by  $\Delta RCF$ .

5. The method of claim 1 wherein,

the battery cell has a maximum allowable voltage  $V_{Max}$  and a minimum allowable voltage  $V_{Min}$ , and

the increasing the  $V_{High}$  and decreasing  $V_{Low}$  step increases  $V_{High}$  by a predetermined trigger level adjustment  $\Delta\%$  times the difference between  $V_{Max}$  and  $V_{High}$  ( $V_{High} = V_{High} + \Delta\% (V_{Max} - V_{High})$ ) and decreases  $V_{Low}$  by  $\Delta\%$  times the difference between  $V_{Low} - V_{Min}$  ( $V_{Low} = V_{Low} - \Delta\% (V_{Low} - V_{Min})$ ).

6. The method of claim 1, wherein the adjusting the  $RCF$  step to center the trigger range comprises the steps of,

determining a current recharge range ( $DVC$ ) for the current recharge cycle,  $DVC$  being the difference between  $VEOC$  and  $VEOD$  ( $DVC = VEOC - VEOD$ ),  $DVC$  becoming a previous recharge range  $DVP$  during a next recharge cycle of the recharge cycles,

determining when  $DVC$  is greater than  $DVP$  indicating an increasing recharge range,

decreasing the  $RCF$  during normal condition in the presence of the increasing recharge range,

determining when  $DVC$  is lesser than  $DVP$  indicating a decreasing recharge range, and

increasing the  $RCF$  during normal condition in the presence of the decreasing recharge range.

7. The method of claim 1, wherein the adjusting the  $RCF$  step to center the trigger range ( $DVT$ ) comprises the steps of,

determining a current recharge range ( $DVC$ ) for the current recharge cycle,  $DVC$  being the difference between  $VEOC$  and  $VEOD$  ( $DVC = VEOC - VEOD$ ),  $DVC$  becoming a previous recharge range  $DVP$  during a next recharge cycle of the recharge cycles,

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determining a decreasing recharge range condition when DVC is lesser than DVP and when a high voltage margin (VH) being a difference between VHigh and VEOC ( $VH=VHigh-VEOC$ ) is greater than a low voltage margin (VL) being a difference between VEOD and VLow ( $VL=VEOD-VLow$ ),

determining an increasing recharge range condition when DVC is greater than DVP and when VH is lesser than VL,

decreasing the RCF during the normal condition and in the increasing recharge range condition, and

increasing the RCF during the normal condition and in the decreasing recharge range condition.

8. The method of claim 7 wherein the increasing the RCF step during the normal condition comprises the steps of,

determining a recharge fraction adjustment portion  $\Delta F$  of a predetermined recharge fraction adjustment  $\Delta RCF$ , and

increasing the RCF by  $\Delta F$  times  $\Delta RCF$ , ( $RCF=RCF+\Delta F \times \Delta RCF$ ), where  $\Delta F$  is a positive value.

9. The method of claim 7 wherein the decreasing the RCF step during the normal condition comprises the steps of,

determining a recharge fraction adjustment portion  $\Delta F$  of a predetermined recharge fraction adjustment  $\Delta RCF$ , and

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decreasing the RCF by  $\Delta F$  times  $\Delta RCF$ , ( $RCF=RCF+\Delta F \times \Delta RCF$ ), where  $\Delta F$  is a negative value.

10. The method of claim 7 wherein the increasing the RCF step during the normal condition comprises the steps of,

determining a recharge fraction adjustment portion  $\Delta F$  of a predetermined recharge fraction adjustment  $\Delta RCF$ , the  $\Delta F$  is equal to a scalar gain (G) times the difference between VH and VL and times a ratio of the trigger range DVT minus VH divided by DVT ( $\Delta F=G(VH-VL) \times ((DVT-VL)/DVT)$ ), and

decreasing the RCF by  $\Delta F$  times  $\Delta RCF$ , ( $RCF=RCF+\Delta F \times \Delta RCF$ ), where  $\Delta F$  is a positive value.

11. The method of claim 7 wherein the decreasing the RCF step during the normal condition comprises the steps of,

determining a recharge fraction adjustment portion  $\Delta F$  of a predetermined recharge fraction adjustment  $\Delta RCF$ , the  $\Delta F$  is equal to a scalar gain (G) times the difference between VH and VL and times a ratio of the trigger range DVT minus VL divided by DVT ( $\Delta F=G(VH-VL) \times ((DVT-VL)/DVT)$ ), and

decreasing the RCF by  $\Delta F$  times  $\Delta RCF$ , ( $RCF=RCF+\Delta F \times \Delta RCF$ ), where  $\Delta F$  is a negative value.

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